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Evaluation of Methods for Solid Propellant Burning Rate Measurement

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ABSTRACT

The NATO Research and Technology Organization (RTO), Advanced Vehicle Technology (AVT), Working Group (WG) 016 (formerly AGARD/PEP Working Group #27) undertook to evaluate methods in use within the NATO propulsion community to measure burning rate in solid propellant rocket systems, with the purpose of identifying similarities and differences between the participating nations. This WG was formed in 1996, consisting of active representatives from 6 of the 15 member nations of NATO, with inputs accepted from 4 other member nations and a couple non-member nations.

The NATO RTO/AVT WG 016 sought to contribute to improvements in the burning rate tools to address issues that have plagued the solid propulsion industry for over 40 years. This paper reviews the final results of this study by summarizing the objectives, approach, findings, and recommendations of this working group based on activity from October 1997 to March 2001. Recommendations are reviewed on direct and non-intrusive burning rate measurement methods, data analysis, and performance scaling to support improved prediction of internal ballistics of a full-scale solid propellant motor.

AVT WG 016 activities have identified that manufacturer burning rate data may not easily be compared without accounting for industry-wide differences in subscale devices, test methods and scaling analysis methods. The WG recommends the NATO propulsion community review these findings as a means of advancing their own burning rate measurement and analysis methods.

INTRODUCTION

Solid Rocket propulsion remains the major propulsion concept for the tactical and strategic missiles, and for many first stage launch systems. Among the parameters controlling the solid rocket motor operation, burning rate plays a very important role.[1,2] The WG 016 sought to provide for a:

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1) Better understanding of burning rate, $r_b(p,T_o)$, data from various facilities to ease the comparison of propellants from various manufacturers and to improve international exchanges and cooperation.
2) Improved measurement accuracy and reliability to allow a decrease in the number of tests (and associated time and cost) and improved control of manufacturing and quality assurance and the assessment of aging.

The WG reviewed and compared methods for measuring steady-state burning rate of solid rocket propellant through current subscale motor practices with an emphasis on data analysis methods and non-intrusive techniques. The WG focus included approximately 70% subscale motors, 25% non-intrusive diagnostics and 5% other methods including strand burners. Members of the WG participated in six technical interchange meetings between October 1997 and October 1999 pursuing the approach: (1) Surveying the NATO solid propulsion community for subscale and non-intrusive test methods, analysis, and scaling methods, and (2) Analyzing "simulated" and "real" motor pressure-time data using multiple thickness/time (TOT) and mass balance (MB) burning rate analysis methods taken from the survey.

Time-consuming survey and analysis support was solicited from a wide range of facilities within the NATO solid propulsion community during the course of this effort. Four separate Analysis Round Robins (RR) were conducted with solicitations for support made to NATO propulsion industry contributors. The influence of various burning behavior was examined in these RRs, such as progressive or regressive burning, constant and random bore offset variations, constant and random L^* variations, and different rate equations. Trends in observed differences in calculated burning rate for the different analysis methods were evaluated for these cases with a WG goal of making recommendations on preferred analysis methods.

The RRs were used in analyzing "simulated" and "real" motor pressure-time data for the purposes of involving the participants in the data analysis, review and discussion, and conclusion process. The WG considered this critical if either voluntary change was to be expected, or resistance to changed procurement specifications forestalled as an outcome of this study. Clearly participation and peer review was integral to these activities. Continuing efforts in this regard are beneficial to understanding the merits of any conclusions drawn from this study.

A complete report of the NATO RTO AVT WG 016 activities is available[3]. Selected findings and recommended practices are reviewed in greater detail in companion JHU/CPIA Chemical Propulsion Technology Reviews (CPTR's), including: 1) test motor performance scaling[4], 2) burning rate measurement test techniques and subscale test hardware[5], and 3) burning rate analysis methods and results of the round robins[6] for accurate prediction of internal ballistics of a full-scale solid propellant motor.

Analysis Round Robin Approach

One approach to isolating the data analysis procedures from the propellant, motor, and instrumentation variations is to generate and analyze simulated motor data for an "ideal" propellant in an "ideal" motor with "perfect" instrumentation. Realism may be approached asymptotically by adding known non-ideal propellant, motor, or instrumentation phenomena.[7]

Burning rate results reduced from the simulated motor data were used to examine two specific questions considered critical to understanding of burning rate measurements: (1) What is the bias (scale factor) and precision (non-reproducibility) of a given analysis procedure when applied to an ideal motor with perfect instrumentation? and (2) What is the effect of non-instantaneous burnout upon that analysis procedure?

Simulation programs were used, or if not available, developed for the specific purpose of exploring the various causes of burning rate measurement bias and precision upon analysis procedures in otherwise "ideal" motors. The WG approached realism alternatively by analyzing "real" motor data to expose any effects artificially induced by using simulated data. The results of multiple analysis RRs and analysis of real motor data are reviewed and findings discussed.

WG 016 Membership and Participants

Dr. P. Kuentzmann of ONERA, France, initiated the WG in 1997 under the former AGARD Propulsion and Energetics Panel (PEP). His early vision as advocate for this effort is appreciated. AVT WG 016 members are listed in Table 1.0.

The WG016 members most gratefully acknowledge the significant contributions of Mr. Richard Hessler, independent consultant to the WG016 from the U.S. Additionally, the WG members are sincerely grateful to the NATO international propulsion community (facilities and their representatives) for their contributions included in this report. Over 50 contributors participated from over 35 companies, universities, and agencies. These contributions included information on test hardware, analysis and scaling methods, and support for multiple analysis RR's of simulated and real motor data. A complete list is provided in the final report.[3]

Table 1.0 NATO RTO AVT WG 016 Membership		
Mr. Ronald Fry (Co-Chairman)	JHU/CPIA	U.S.
Dr. Robert Frederick	Univ Alabama in Huntsville	U.S.
Mr. Rene Couturier(Co-Chairman)	SNPE	France
Mr. Dominique Ribereau	SNPE	France
Mr. Jean-Paul Reynard	ONERA	France
Mr. Jean-Claude Traineau	ONERA	France
Dr. Hans-Ludwig Besser	Bayern-Chemie	Germany
Dr. Rudiger Strecker	Bayern-Chemie	Germany
Prof. Luigi DeLuca	Politecnico di Milano	Italy
Dr. Guy M.H.J.L. Gadiot	TNO PML	Netherlands
Mr. Tony Whitehouse	Royal Ordinance	UK

BURNING RATE FUNDAMENTALS

Burning rates of solid propellants, whether steady or unsteady, under a variety of operating conditions is of critical importance for applications (due to their sensible influence on performances and cost of propulsive devices) and for fundamental reasons (understanding of combustion processes). Furthermore, since no available theory/model is capable of predicting burning rates with accuracies within 1% and including the effects of rate modifiers, they must be measured experimentally. However, while experiments measuring steady burning rates are reasonably robust, those measuring unsteady values are fragile and still a matter of research. Since a variety of experimental hardware and procedures are in use today, even for the common steady-state operations, the need arises to understand and perhaps standardize the different approaches developed among the NATO countries.

The fundamental physics, features, empirical laws and analytical models, stability measurement methods, and scaling of burning rate are reviewed in the report. Analysis results in this study are expressed in terms of the simple power law rate equation[8], often referred to as the St. Robert's, St. Venant's or Vielle's law, $r = ap^n$.

Two basic classes of empirical burning rate definitions are in use for motor applications. These two families of fundamentally different burning rate determination each have their advantages and disadvantages. The definitions are explored further in the analysis of subscale motor test data, reviewed in detail later. One definition is based on propellant thickness and the burning time and is referred to as the thickness/time (TOT) method, and the second definition is based on the conservation of mass in the ballistic test motor and is accordingly termed mass conservation or mass balance (MB) method.

The conventional burning rate definition is the fundamental TOT rate, r_{TOT}

$$r_{TOT} = \frac{web\ thickness}{burning\ time} = \frac{w_b}{t_b} \qquad (1)$$

requiring the appropriate but elusive value of thickness besides that of the related time. Real world effects such as non-uniform web and non-instantaneous burnout make accurate measurements of burning rate difficult. In attempting to correct for these factors, an alternative definition evolved based on some approximation of the mass conservation equations.

MB methods evaluate the steady burning rate r_{MB}, indirectly from the balance between mass flow input from the burning propellant and output through the nozzle throat. Burning is assumed to occur throughout motor operation, implicitly accounting for non-instantaneous burnout. Mass conservation should include gas storage in the combustion chamber due to density change and/or volume change; accordingly, several versions of this approach exist. The MB rate, neglecting corrections, features less data scattering than the TOT rate, because it partially corrects for non-instantaneous burnout[9,10]

Neglecting gas storage in the combustion chamber due to density change and/or volume change, an (average) MB rate r_{MB} is written as (see Figure 1 for notation definitions)

$$r_{MB} = \frac{w_A - w_G}{t_E - t_B} \frac{\int_B^E p_c dt}{\int_A^G p_c dt} = \frac{w_{avg}}{t_b} \frac{\int_B^E p_c dt}{\int_A^G p_c dt} \qquad (2)$$

COMPARISON OF TECHNIQUES/DEVICES

Measurement Test Objectives

The burning rate at a certain pressure and the burning rate behavior over a pressure range is a characteristic property of a solid propellant. Typically, subscale test motors are used to determine this property of a propellant during its life cycle (i.e. during research, the initial selection phase for a certain application, in the development and qualification phase of a rocket motor, as batch control during production, and aging studies to determine useful motor life).

The objective for determining this specific property is different for propellant researchers and design, development and production engineers. The influence of new ingredients and new formulations on the burning rate is most interesting to the propellant researcher. Design, development and production engineers, however, are more interested in the applicability and reproducibility of a propellant with this specific property. The measurement test objectives of propellant burning rates can therefore be subdivided into various phases, research and technology, screening, development, performance verification and production control.

International Facility Survey

A survey was conducted among the participating and non-participating NATO countries. Twenty-three various propellant manufacturers and institutions from industry, governmental laboratories and universities were asked to describe their motors or devices used to evaluate burning rates of solid propellants. The survey is discussed in the final report. Complete test hardware details and drawings are provided in Annex A of the final report[3] and JHU/CPIA, CPTR-74[5].

The wide array of motors for burning rate determinations of the different countries are summarized in Table 2.0 using a somewhat arbitrary differentiation in motor weight classes.

Table 2.0 Summary of Motors from International Survey

Users		Number of Motors in Use				
Region	Number of Facilities	I <200g	II 200-500g	III 500-5,000g	IV 5,000-10,000g	V >10,000g
CA / US	14	8	12	7	3	4
European	9	4	8	8	2	1
Totals	23	12	20	15	5	5

The predominant configuration encountered is the circular, center perforated grain in the weight Classes I - III. The motors in weight Class IV and V with grain weights up to 60 kg should not be considered subscale test motors normally used for general purpose burning rate determinations. Rather, these motors are test vehicles for very large boost motors for space or strategic applications.

A historical survey by Fry[11] in the mid-1990s examined burning rate measurement practices employed in the U.S. solid propulsion industry. Subscale motors in use in the U.S. at that time are summarized in Table 3.0. A comparison of motors in use in the U.S. in the mid-190s (Table 3.0) with those in use today (Table 2.0) suggests there are fewer facilities in the U.S. today using more Class I and II motors, fewer Class III and IV motors, and the same number of the largest Class V motors.

Table 3.0 Summary of Subscale Motors from U.S. 1995 Survey[11]

U.S. Users		Number of Motors in Use			
	Number of Facilities	I-II <200-500g	III 500-5,000g	IV 5,000-10,000g	V >10,000g
Industry	23	5	11	7	4
Government	9	4	2	3	-
University	8	3	1	1	-
Totals	40	12	14	11	4

The international facility survey revealed that all manufacturers are using specially designed devices to determine burning rates of propellants. Principally, all devices have the same design and differ only in size. An example of the most widely used subscale test motor is the 2x4-inch motor (Figure 1.0) described in detail below.
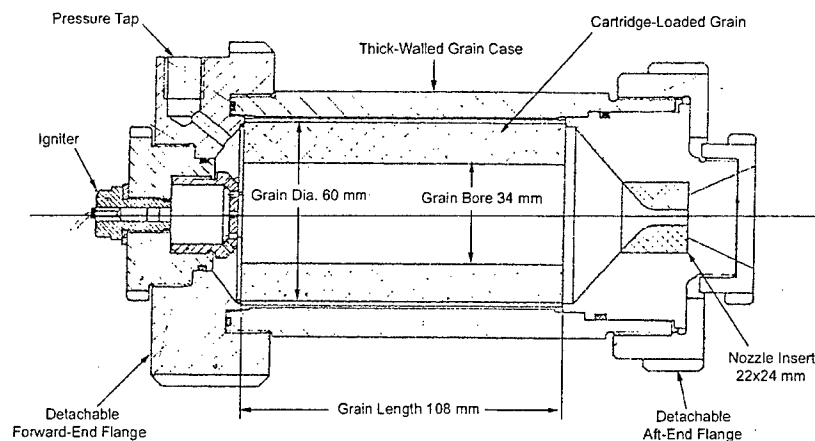
Fig. 1.0 Typical 2-Inch Subscale Test Motor

The typical subscale test motor consists of a thick-walled tube and in most cases of two flanges. This design facilitates easy cleaning and allows the motor to be used repeatedly. Many facilities use a cartridge-loaded grain configuration for this purpose. The forward flange is equipped with one or two pressure taps, and also contains the housing for the ignition device, i.e. squib and ignition materials, if center perforated grains are used. For endburning grains, the ignition device is mounted on the aft-end flange. For safety reasons, a pressure relief mechanism is sometimes used which is a calibrated burst diaphragm yielding at a pressure equal to the design pressure of the heavy walled motor. It is mounted either on the forward or aft-end flange. The aft-end flange mainly consists of or holds the nozzle inlet and exit cone with a provision for an exchangeable nozzle throat insert, which is generally made of graphite. Other materials, such as steel, molybdenum, tungsten, or TZM are sometimes used, depending on the type of propellant to be tested. This generic heavy-duty small-scale test motor can be used to test propellants with various grain configurations, which can be subdivided into three groups:

1. Center perforated grains with a tube or star configuration, flat or conical, forward and aft end, and inhibited or uninhibited outer diameter
2. Endburning circular grains or discs
3. Uninhibited rectangular slabs of propellant, burning at all six surfaces

Group 1 and 2-grain configurations give a neutral burning behavior and are used for single point firings of the burning rate/pressure characteristic (r_b/p-function) of a propellant. By varying the nozzle throat, the burning rate of the propellant is determined over the desired pressure and temperature range. The stepped, circular end burning grain and the group 3-grain configurations are used in the multiple points firing method, where a pressure range is covered with one firing only.

The WG created a summary of the use of burning rate measurement hardware in relation to the life cycle of the propellant versus its application. The smaller Classes I-III are used in the research/technology, screening and development phases for both tactical and space/strategic propulsion. It emphasizes again, that the large subscale test motors in Class IV and V are mainly used in the screening through performance verification phases for space/strategic applications. For more details, see Annex A of the final report[3] and JHU/CPIA, CPTR-74[5].

Test Method Recommendation

The international survey revealed, that the 5x10 cm (2x4 inch) motor containing a circular center perforated grain is the most widely used tool to determine the burning rates of composite propellants. Unfortunately, this motor is not standardized with respect to dimensions and propellants mass, which varies between 120g - 450g. In order to enhance comparability and accuracy, the WG recommends standardizing this motor by lifting it into the grain weight Class No. II. This can be accomplished by simply increasing the web of the propellant grain to nominally 13mm, resulting in a propellant weight of approximately 300-400g. This would cover the majority of propulsion applications. Propellants for space and strategic propulsion applications will always be an exception and should therefore be tested with the larger motors.

Recommended burning rate measurement practices, including test hardware, instrumentation, and data reduction are summarized in more detail in the final report. These practices expand upon and are consistent with recommendations of the 1970-71 works of Miller & Barrington[17] and NASA SP-8039[12]. WG 016 findings are consistent with Miller & Barrington who suggested Class III motors, 2000g-5000g provides satisfactory scale-up for smaller full-scale motors (D ≤ 76 cm). Several examples of these Class III motors are available with 6 countries and 11 facilities having this capability. The AFRL BATES motor and the ARC Rohm and Haas 6C4 / 6C5 motor are classic examples. The largest motors in weight Class V with grain weights from 22kg up to 60 kg permit satisfactory scaling for very large boost motors for space or strategic applications. The confidence and accuracy of predictions are possible by establishing a correlation between full-scale motor performance, subscale test motors, and liquid and solid strand burning rate tests that remains constant, as reviewed in detail below.

COMPARISON OF ANALYSIS METHODS

Our understanding of burning rate analysis methods can be improved by examining practices employed by various facilities and countries engaged in the measurement and analysis of burning rate in solid propellant systems. Over 20 facilities from 7 NATO member countries were surveyed for their methods used and their characteristics. Annex B to the final report[3] and JHU/CPIA, CPTR-75[6] contain details of the data analysis methods surveyed. This is a complete survey of all major international facilities involved in burning rate measurement, and a thorough representation of the fundamental methods used in the solid propulsion community today. The fundamental means of determining burning rate and basic definitions are reviewed first, focusing upon methods encountered in the international survey. Results of the international survey are summarized and findings discussed.

Description of Methods

Fundamental Definitions
The two families of burning rate determination methods described earlier may be further divided into the following categories, which are more descriptive of their specific application:
1. Thickness/time (TOT) Methods
    a) TOT Rate, r_{TOT}
    b) Iterated TOT Rate, r_{TOTn}
    c) Iterate Two-Point TOT Rate, r_{HG}
2. Mass Balance (MB) Methods
    a) MB Rate, r_{MB}
    b) Iterated MB Rate, r_{MBn}

The iterated procedures differ in the use of the rate-averaged instead of the more common time-averaged pressure and an iteration to determine exponent n. While r_{TOT} is in error when burnout is non-instantaneous (as usually observed), r_{MB} is in error if mass storage is neglected. The HG (Hessler-Glick) r_{TOT} procedure, initially developed for reference purposes in support of WG 016 in the mid-1990s[13,19], avoids both errors by explicitly recognizing non-instantaneous burnout. Only the HG reference method enforces a set of derivative-based time point definitions following a careful analysis of the physics of motor operation. Two r_{TOT} measurements are made using the average web thickness, r_{bi} using an initial burnout time definition t_{Ei}, and r_{bf} using a final burnout time definition t_{Ef}.

Representative MB methods currently in use by facilities surveyed by WG016 include:
1. Common MB Method
2. Vellacott's Method
3. Brooks' Improved Method
4. Jordan's Combined MB with TOT Method

The common MB neglects all storage terms, as described by Equation 2. Vellacott's method includes a correction for mass storage due to volume increase. The Brooks' improved MB method approximates all storage terms, including correction due to a changing pressure as well as volume. Jordan's combined method simultaneously solves for the MB and TOT burning rates, assuming only one burning rate properly defines the propellant, regardless of the method.

Grain Web Thickness Definitions
Grain web typically used for burning rate calculation is usually one of the following:
1. Drawing dimensions,
2. Drawing dimensions corrected for theoretical shrinkage, or deformation
3. A measured "average".

While each choice yields an "average" thickness, the difference between the choices on the results can be considerable. Improved accuracy can be obtained by measuring grain bore and case inside diameters. Diameter measurements 1 – 2 web thickness into the grain bore essentially eliminates most of the web bias caused by taking measurements at the grain ends. The thinnest point is usually near the center. Moreover, mandrel roundness, straightness and alignment imperfections can result in up to 10% web

bias over drawing dimensions and result in inaccuracies for the burning rate of up to 3%. When a grain is cast into phenolic sleeves or into a steel case with relatively thick liners on the inside surface, the grain outside diameter is rather difficult to determine and simultaneously the web thickness, again increasing inaccuracy.

Burning Time Definitions

The motor action time follows from the pressure-time trace, which starts at the beginning of motor operation, and ends at the end of motor operation (see Figure 2.0). The burning time is determined from this trace as the period from the moment that all propellant is considered burning until the moment the web is considered consumed. For burning rate determination, the burning time is the appropriate time period to use.

The following burn time definitions were encountered in the survey:
1. Constant P or %P_{max} - 10%, 50%, 60%, and 75%, with 10 % typical
2. Tangent-Bisector
3. Brimhall - $d^2P/dt^2 = 0$ or a maximum negative dP/dt during tail-off
4. Brooks' - Pressure Integral
5. Hessler-Glick - from the first perceptible rise on the *last sustained rise* to *a negative step* of d^2p/dt^2 to negative value (t_{Ei}), and to *a positive step* of d^2p/t^2 to positive value (t_{Ef}).
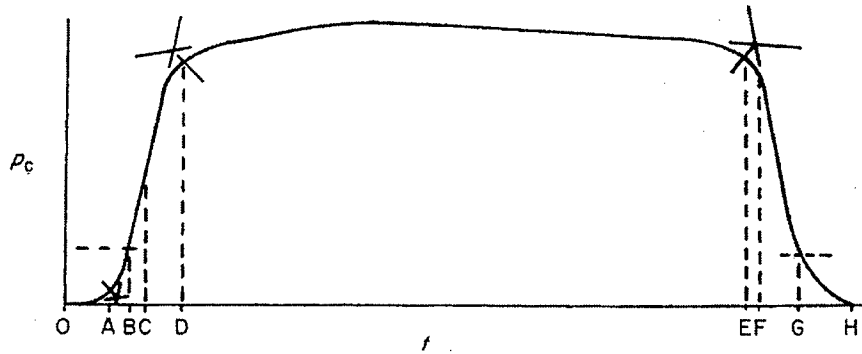

Figure 2.0 Various Burning Time Definitions[17]

Average Pressure Definitions

The pressure usually associated with a measured burning rate is the *time-averaged pressure*

$$p_b = \frac{\int_{t_B}^{t_E} p \, dt}{t_E - t_B} \tag{3}$$

However, any measured point [r_{meas}, $p(r_{meas})$] must also simultaneously satisfy the power law rate equation, which requires use of *rate-averaged pressure*[14, 15, 16]

$$p(r_{meas}) \equiv p_{nb} = \left(\frac{\int_{t_B}^{t_E} p^n \, dt}{t_E - t_B} \right)^{\frac{1}{n}} \tag{4}$$

Comparison of Analysis Methods

Many r_{TOT} procedures do not explicitly account for non-instantaneous burnout. In fact, r_{TOT} procedures typically define end of burning as the knee of the curve (web burnout), when the experimental pressure trace begins to fall rapidly near the end of motor operation. However, specific choices of time points may make the correction implicitly. Procedures that define end of burning near 50% pressure implicitly assume burning continuation and thus partially avoid non-instantaneous burnout error, but not as well as an r_{MB} definition that actually uses the integral ratio. Due to transient operations, these r_{TOT} procedures tend to behave essentially like r_{MB} procedures. While use of 50% pressure time points for start of burning only has small effect on burning rate, the choice of 50% or more for end of burn during pressure decay can be a source of higher rate bias. A drawback of a 50-50 definition is that the time-averaged pressure differs much more from the rate-averaged pressure because the ending points are much lower

down on the tailoff curve than for an equilibrium or web-knee definition. More bias in burning rate is introduced, as the rate-averaged pressure is seldom used.

r_{MB} methods yield rates that are systematically low by a mass storage error. In turn, mass storage error also introduces a systematic nonlinearity in measured $r_b(p)$. Procedures essentially behaving like r_{MB} are likewise low by a mass storage error and generate similar nonlinearities. HG fully avoids the mass storage error, so it will be linear and systematically yield higher rates than r_{MB} procedures. r_{TOT} methods, with instantaneous burnout, also avoid the mass storage error yielding negligible nonlinear errors but high bias due to non-instantaneous burnout.

International Survey of Analysis Methods

Three historical surveys exist of burning rate analysis practices employed in solid propulsion industry. One conducted by Miller and Barrington[17] in the late 1960s, a second conducted by Brooks and Hermsen[18] in the late 1970s and the last by Fry[11] in the mid 1990s. Trends suggest the fundamental TOT procedures are being replaced by MB procedures or TOT procedures with burning times evaluated using pressure integrals.

Our understanding of analysis methods is further improved by examining the current practices employed by the 21 facilities from 7 NATO member countries surveyed by the WG016. The data analysis methods are given in Table 4.0. This table summarizes the source of the method by country and facility and the fundamental type. Detailed descriptions of the methods are provided in Annex B of the final report[3] and JHU/CPIA CPTR-75[6].

Table 4.0 Summary of Data Analysis Methods

COUNTRY	FACILITY	METHOD
CANADA	DREV	r_{TOT}
FRANCE	SNPE / ONERA	r_{TOTn}
GERMANY	BAYERN-CHEMIE	r_{TOT}
ITALY	FIAT AVIO	r_{TOTn}
NETHERLANDS	TNO-PML	r_{TOT}
UK	RORM	r_{TOT}
U.S.	Aerojet	r_{TOT}, r_{MB}
	AFRL / PLE	r_{TOT}
	Alliant Tech Systems	r_{MB}
	AMCOM	r_{MB}
	Atlantic Research Corp	r_{MB}, r_{MBn}
	BF Goodrich/Univ Prop	r_{TOT}
	GD/Ord & Tech Sys	r_{TOT}
	NAWCWD China Lake	r_{TOT}, r_{MB}
	NSWC	r_{MB}
	P&W / CSD	r_{MB}
	SNAP/Jordan	r_{MBn}
	Stone Engineering	r_{MBn}
	Talley Defense Sys	r_{TOT}
	Thiokol Propulsion	r_{TOT}, r_{MB}
Reference	Miller & Barrington	r_{TOT}, r_{MB}
	Hessler/Glick (HG)	r_{HG}

Review of these data indicates all 7 European facilities use TOT procedures, with approximately half using burning end time definitions that try to account for non-ideal tailoff. Slightly more than half the U.S./Canada facilities use MB procedures, while the majority use burning end time definitions that try to account for non-ideal tailoff. Some facilities possess both TOT and MB capabilities for use in different motor test situations. Over 90% of all facilities surveyed use a simple constant P or %P to define burning

start time. Large variability in burning end time definition is seen. This type of variability in definitions makes assessment of the analysis methods difficult.

Assessment Using Simulated Motor Data

The RTO/AVT WG016 assessed the various TOT and MB analysis methods taken from the international survey for the purposes of (1) Clarifying distinctions of subscale motor analysis methods, and (2) Identifying sources of the differences. The assessment using simulated motor data involved carrying out four Round Robin (RR) evaluations. Each RR was essentially carried out as a blind experiment, where individual participants were given minimal knowledge of the motor geometry and no information on the propellant-burning rate behavior. The design and execution of the RR #1 and #2 simulations were found to embody properties that placed limitations on the conclusions that could eventually be drawn from the results. These issues are reviewed individually with the discussion of each RR. As a result, RR #3 and #3X were designed and executed to overcome these shortcomings.

International RR #1 Results

RR #1 is based on a spreadsheet program derived from a relatively straightforward simulation of a simple end-burning grain. RR #1 consisted of four pressure-time traces for the burning cases of neutral, progressive, regressive, and progressive with noise. Analysis results for RR #1 data were received in mid-1997 from the following 11 volunteer participants: ONERA, SNPE, Bayern Chemie, TNO-PML, Aerojet, Alliant Tech Systems, (formerly Hercules), NSWC, SNAP/F. Jordan, Talley Defense Systems, Thiokol, and R. Hessler. Eight of the participants used TOT procedures, while 3 used MB analysis procedures. Data shows the burning rate was generally over-predicted by 2-4%, with the majority of the participants showing a 1-2% deviation. The power law exponent was typically under-predicted by 1-5%, with a couple outliers. Due to the limitations of the simulation, conclusions on the relative merits of the end of burning definitions and conclusions on the relative merits of TOT and MB burning rate definitions are unwarranted. Despite these limitations, the following conclusions may be drawn: (1) Definitions for the beginning of burn time using the first derivative minimum yield the most accurate and approximately the lowest rate and highest exponent. The definitions based on fractions (0%, 10%, and 50%) of P_{max} are *ad hoc* definitions resulting in monotonically differing values of rate (increasing) and exponent (decreasing); and, (2) Reference rate values based on the theoretically defined time-averaged pressures are higher than those based on rate-averaged pressure, while the pressure exponents are lower for time-averaged than for rate-averaged pressures.

International RR #2 Results

RR #2 is based on Solid Performance Program (SPP) Version 7.0 simulations of simple 2x4-inch motor ballistics. RR #2 consists of twelve different simulated pressure-time traces for the cases representing the successive addition of different motor perturbations: baseline; baseline with increased L*; baseline with added igniter effect; baseline with added igniter effect and erosive burning; baseline with added igniter effect, erosive burning and nozzle erosion; and, baseline with added igniter effect, erosive burning, nozzle erosion and bore offset. Each pair of cases represents a high and low-pressure case for otherwise identical motors. RR #2 responses were received in early-1998 from the following ten volunteer participants: ONERA, SNPE, Bayern Chemie, TNO-PML, Royal Ordnance, NAWCWD, NSWC, P&W/CSD, SNAP/Jordan and R. Hessler. Six of the participants used TOT procedures, while four used MB analysis procedures.

While flaws in the simulated RR #2 dataset hamper definitive discrimination among timepoint definitions and among burning rate procedures, some general trends are suggested. The RR #2 results did not recover the reference-burning rate that was input to the SPP simulation. The burning rates and burning rate coefficients were over-predicted, while the exponent was slightly under-predicted, but within 1%. All analysis methods yielded an average deviation of 0.5% relative to the baseline for the cases of high L* data, the influence of ignition, and erosive burning. However, a deviation in burning rate for the TOT methods of 4 - 18% relative to the baseline rate for the nozzle erosion and off-axis bore cases. The deviation for the TOT methods with respect to the reference rate is even larger. The deviation in burning rate for the MB methods remained at less than 1% for all the cases examined. The MB methods seem to provide better agreement when compared with either the baseline or the reference burning rate, exponents or coefficients.

When evaluating the web burned during each test, it was observed that unburned web remained in all tests. More web remained at the low pressure tests than at the high pressure tests. Corrections were made to the web for one of the data reduction methods (TNO method) and the data were reduced for the actual web burned. The results are considerably better with less than 0.2% deviation for all cases except for the L* case, which was about 0.8%. These results actually prove that proper knowledge of the actual web burned is very important for determining the burning rate and burning rate relation correctly.

The nature of the RR #2 design also attempts to answer what effects perturbations in motor parameters have. While the trends appear consistent, due to the flaws in the dataset, caution should be exercised in making too much of the reported results.

International RR #3 Results
RR #3 is based on a computer program, created by R. Hessler and R. Glick in support of the WG 016, to generate simulated motor data for research into burning rate measurement methods.[7] RR #3 consists of ten different pressure-time traces for 5 baseline and 5 off-axis bore cases. Ten pressure-time histories comprising two groups simulate generic 2x4-inch motor behavior. Each group contains five motors, equally spaced in log pressure. RR #3 responses were received in early-1999 from the following 18 volunteer participants: DREV, SNPE, Bayern Chemie, POLIMI, TNO-PML, Royal Ordnance, Alliant Tech Systems, AMCOM, ARC, BF Goodrich, NAWCWD, NSWC, P&W/CSD, SNAP/Jordan, Stone Engineering, Thiokol, and Hessler. Nine of the participants, Canada, the European facilities, Thiokol, and R. Hessler used TOT methods to reduce the data and determine the propellant burning rates, while the remaining nine participants from the U.S. used MB methods. Lessons on RR #3 and #3X are summarized below.

International RR #3X Results
RR #3X is also based on the Hessler-Glick ballistic simulation of a 2x4-inch motor configuration. RR #3X consists of 40 additional cases, arranged in eight groups of simulated rocket motors beyond those examined in RR #3. These additional groups are mainly perturbations of the original RR #3 Group 2, which had constant bore offset. These groups are designed to examine the effects of non-neutrality, L*, further bore offset perturbations, and of higher rate, pressure, and exponent. Data typically unknown, such as the burning rate equation, bore offset, and randomized parameters were withheld from the participants. RR #3X responses were received in late-1999 from POLIMI, who analyzed the cases using TOT methods from Bayern Chemie and Hessler.

Lessons from the Round Robins
RR #3 and #3X tests have pointed out the quality of applied data reduction methods for a change of several parameters (bore offset, characteristic length, non-neutral trace shape, rate equation, etc.) influencing combustion. Results from different procedures were compared with the rate equation used for the simulations and with each other to identify the following systematic errors inherent in the various procedures:[16,19]

- Non-Neutrality Error: Present whenever time-averaged pressure is used as the associated pressure (r_{TOT} and r_{MB}). Caused by non-constant pressure during burning. Corrected by use of rate-averaged pressure as the associated pressure (r_{TOTn}, r_{MBn}, and r_{HG}).

- Non-Instantaneous Burnout Error: Present in principle in TOT procedures (r_{TOT} and r_{TOTn}). Caused by web thickness variations within individual motors. Avoided by use of MB procedures (r_{MB} and r_{MBn}). Corrected by the iterated two-point TOT procedure (r_{HG}).

- Mass Storage Error: Present in MB rate procedures (r_{MB} and r_{MBn}). Caused by neglect of mass storage in MB rate definition. Avoided in principle by TOT procedures (r_{TOT} and r_{TOTn}). Fully avoided by the iterated two-point TOT procedure (r_{HG}). Correctable by accounting for transient operations, but some unknown residual error will remain due to invoked assumptions. The Non-Neutrality error and Mass Storage error, being roughly proportional to pressure, cause nonlinearity in the measured log rate versus log pressure relationship. This nonlinearity causes the measured pressure exponent n to appear slightly pressure dependent.

The r_{HG} procedure avoids all three of the errors above, obtaining data accurate to the basic time resolution of the simulations. Thus, in treating simulated pressure traces, HG proved superior to other methods due to a careful set of time points definitions, but requires visual inspection of each pressure trace.

The error levels in the reduced data were appreciably smaller than the suspected bias in real motors, evidenced by observation that burning rate in small motors is commonly of order 5% less than in larger scale end-item motors. However, these were *simulations*, and the simulations did *not* include several phenomena that occur in real motors. In particular, the simulation program assumed instant, effortless ignition in an adiabatic chamber, with burning immediately occurring at the equilibrium burning rate for the bulk propellant. In real propellants and motors, heat losses and the transients associated with the development of equilibrium burning extend the pressurization phase of the motor by a factor of two to five. The slower pressurization rate will cause the Non-Neutrality error to be increased by about the same factor. Similar transient phenomena will extend the tail off process, causing the apparent Mass Storage Error to be similarly inflated. Observation that both errors cause rates to be underestimated suggests they may be large contributors to observed rate scale factors.

Assessment Using Real Motor Data

Data reduction methods were contrasted[20] to analyze the Baria (6300g) and 2-inch (350g) experimental pressure traces used to evaluate the ballistic parameters respectively for Ariane-5 and Ariane-4 solid propellant boosters. For more test hardware details, see Annex A of the final report[3] and JHU/CPIA, CPTR-74[5]. Fiat Avio – Comprensorio BPD, located at Colleferro, near Rome, Italy, conducted all tests in early-2000. Four series of 9 mixes were made for Ariane-5 and, for each mix; burning tests at 3 different pressure levels were conducted for a total of 108 Baria motor tests. Likewise, a series of 4 mixes were made for Ariane-4 and, for each mix, 6 burning tests (2 at each of the 3 tested pressures) were conducted for a total of 24 2-inch motor tests. For a matter of space, mainly the four series of Ariane-5 mixes are discussed. Comparative analyses were conducted in a series of M.Sc. Theses completed at Politecnico di Milano (POLIMI).

Observed Trends in Analysis Methods

With good quality data and based on mix-to-mix variation, the POLIMI generic MB procedure (based on the U.S. NSWC MB method) and the HG two-point TOT procedure resulted in smaller data scatter than the tested industrial procedures. TOT methods (BC, BPD-1, SNPE) routinely used by European industry produce quite similar values; SNPE and BPD-2 (a variant of BPD-1) offer slightly smaller data scatter and provide almost identical performance; BPD-1 is superior in dealing with Ariane-4 small-scale test motors; and, BC produces reasonable results with little effort. The manual HG and simple POLIMI procedures often showed better performances overall.

The industrial methods nominally assuming instantaneous burnout (BC, BPD-1, BPD-2, SNPE) produce mean values that are quite similar, as expected from the general similarity of these procedures. Within this group, BPD-2 and SNPE (which differ only in details) produce about the same mean values, while BC produces reasonable results with little effort. Relative to the industrial methods, the generic MB procedure used by POLIMI produces lower rates and lower exponents; HG produces higher rates and lower exponents. HG and POLIMI procedures in general also yield relatively more confined values of standard deviation for the ballistic parameters n and a. Most of these observed differences appear to be explainable in terms of known physical effects.

Time-averaged pressure is greater than rate-averaged pressure (consistent with RR #1 results), so any procedure using time-averaged pressure yields a rate equation that is consistently biased low due to the Non-Neutrality Error. As HG is the only procedure using rate-averaged pressure as the associated pressure, HG rates are expected to be higher than the others. In general, for a fixed average degree of non-instantaneous burnout due to either grain distortion or misalignment, the Non-Neutrality Error for a propellant will increase at lower pressures, because the burnout process extends for a greater fraction of the tail-off process. As a consequence, procedures that use time-averaged pressure should be expected to yield rate equations with exponents biased high, while HG exponents are expected lower.

In treating simulated pressure traces, HG method did best; but while other methods are automated, HG requires some insight and the operator's analysis for each trace. In simulated motors, the HG procedure is not affected by non-idealities of burning process (such as nozzle erosion, non-instantaneous burnout, mandrel eccentricity or bore offset, etc.) and proved to be a reliable method in terms of reproducibility and accuracy of burning rate results. This could not be stated with the same confidence in real operating motors where noise, imperfect instrumentation setup, and different environmental conditions are to be handled. In real test motors, non-idealities in principal favor the class of MB over TOT methods and somewhat compromise the accuracy demonstrated by HG in ideal cases.

Future Work
As to future work, efforts are being made at POLIMI and Fiat Avio BPD to develop an automatic HG procedure to be implemented on standard desktop computers for the benefit of industrial manufacturers. At the same time, refinements in progress of the HG and POLIMI procedures promise to further improve the good performances already shown. In both cases, a relevant benefit could also be gained by further refining the experimental setup and/or test conduction in order to reduce motor variability. More sophisticated statistical analyses of the raw and deduced data are already in progress.

NON-INTRUSIVE TECHNIQUES

Non-intrusive techniques, those that do not perturb the combustion process, have been *demonstrated* on propellants in combustion bombs and some motor applications. While many of these techniques were developed to measure transient combustion,[21] the methods certainly can be applied to the steady-state measurement. Objectives of this effort were to: a) review the most promising non-intrusive methods, b) compare subscale motor and non-intrusive test data, and c) analyze the limitations of the non-intrusive methods and define improvements. Techniques reviewed in the final report include ultrasonics, x-ray, microwave, plasma capacitance gages, acoustic emission, and laser recoil.

International Survey of Techniques

The WG surveyed the member countries on non-intrusive measurement techniques employed currently or in the past. The survey requested 1) the motivation for using the technique, 2) the characteristic strengths and weaknesses, 3) example applications, 4) assessment of advantages, limitations and future prospects, and 5) a list of reference documents. Table 5.0 summarizes the responses from the participating nation. Since these non-intrusive techniques are generally research-oriented, past work has been more focused on development rather than industrial application. The WG therefore obtained much of the information from published literature.

Table 5.0 NATO Survey on Non-Intrusive Methods

Technique	FR	GE	IT	NE	UK	US
Ultrasonics	Y	N	N	Y	N	Y
X-Rays	Y	N	N	-	Y	Y
Microwaves	Y	N	N	-	N	Y
PCG	Y	N	Y	-	N	Y
AE	N	N	Y	-	N	Y
Laser Recoil	N	N	Y	-	N	Y

Y - Yes, N – No burning rate measurement capability

Review of Techniques

Review of each non-intrusive technique in the final report includes a fundamental description, identification of countries and facilities employing the technique, a summary of their industrial experiences, and an assessment.

Ultrasonic
The use of the ultrasonic pulse-echo technique has been applied for over 40 years for the measurement of fuel and propellant burning rates. Twelve facilities in five countries were found to have ultrasonic

measurement capabilities: France, ONERA, SNPE; Netherlands, TNO/Delft University; U.S., AEDC, Lockheed, PSU, Thiokol, UAH, UIUC, and VPI; India, Vikaram; and Sweden, Svenska Flygmotor AB. The industrial experiences applied to motors and closed and open combustion bombs are reviewed in detail in the final report. The results have included steady state ballistic parameters, propellant temperature sensitivity, and erosive burning characteristics.

Applications in combustion bombs have verified the utility of measuring the burning rate at temperatures and pressures representative of rocket motor applications. The closed bomb methods yield an estimate of the complete burning rate law with as little as 30 grams of propellant. This is an advantage in propellant research when small quantities of new ingredients are available for mixing. It has also been demonstrated to batch check small amounts of uncured propellant. This clearly saves the quantity of tests required for strand burner experiments to determine the same information.

In small and large motor applications, ultrasonic instrumentation has been demonstrated several times. In hybrids, it has been used to determine fuel regression rates. On solid rockets it has been used to determine the propellant burning rate and also insulator erosion characteristics. Special practical considerations have been addressed for motor applications such as: gaining good acoustical access to the propellant through the chamber wall, multiplexing data from multiple sensors, and selecting frequencies for deeper penetration.

In general, the technique is capable of measuring the web thickness of composite propellants at depths of up to 30 mm, at pulse rates up to 5000 Hz, over temperature ranges from -40C to 60C. A variety of materials are possible including binders, pure oxidizers, fuel-rich propellants, double base propellant, composite propellant, aluminized (up to 40%) propellant, and insulator materials.

The applicability of the results appears good at this time. Estimates of the measurement uncertainty of this technique range from 1-5% for propellant applications and from 5-10% for hybrid fuel applications or propellant transients. The uncertainty stems mainly from the calibration of the initial length and properties of the propellant as well as the measurement of the echo time. Uncertainties can also arise due to changes in the waveform due to property changes at the propellant surface and weakening of the signal by increased thermal penetration depth. In hybrids, uncertainty arises due to the extended thermal wave and its influence on the acoustic properties of the material. Comparing steady state results of composite propellants tested in a closed bomb with results from small test motors are very encouraging.

The main limitation that prevents further industrial application of the ultrasonic method is the initial training and equipment buildup time for personnel to become experienced with this method. The propellant grain or sample and its coupling material have to be prepared carefully to obtain good ultrasonic echoes. The ultrasonic method can increase the productivity by limiting the test number and the grain masses involved, the burning rate being obtained from only one test (or two) in a large pressure range. SNPE, the French propellant manufacturer, is working on this subject in terms of an industrial procedure application.

X-Ray
X-Rays have been used in a wide variety of configurations to study the behavior of solid propellants. The motivation has generally been to look at dynamic events inside of the motor in a qualitative way. Burning rate data are possible, but the acquisition is relatively expensive and data interpretation is labor intensive. Use of this diagnostic on routine bases holds good promise and would require motor hardware specifically designed to allow transmission of x-rays and the development of automated image processing tools. For now, the utility is in the isolation of specific and unusual transient events or in research. Burning rate resolution at best is 3-5%.

Microwave
The microwave technique has been applied mostly to pressure-coupled response function measurement purpose in the U.S. and in France. This technique requires a specific setup that is far from being applicable to standard burning rate measurement methods. Meanwhile the results provided on both steady and unsteady regimes of combustion were ranked as very satisfactory if some care is taken in the installation of the propellant sample and in the data processing software. The major drawback of this

approach is that it requires a costly device and significant personnel training before being fully operational. It must then be referred to as a research tool rather than an industrial tool.

A recent publication[22] has demonstrated use of the microwave method in a different way to obtain steady-state burning rate measurements under varying pressure and for different initial temperature with satisfactory reported results. Using a main grain generator and a sample on which the microwave measurement is made this technique presents the advantage of being representative of the actual burning conditions in a real subscale motor. This approach seems to use a device and software simple enough to be considered very encouraging.

The microwave technique also offers the potential for measuring *instantaneous* burning rate *differences*. This is achieved by replacing the usual "fixed" termination for the reference wave with a second grain. The advantage is that a direct burning rate sensitivity measurement is obtained (roughly 40% accuracy improvement). Potential applications would be to temperature and formulation sensitivity measurements. In a closed burner these could be made over an extended pressure range in a single burn. Similar measurements could, in principal, be made with ultrasonic techniques.

Plasma Capacitance Gage
The PCG technique has been applied mostly for insulation erosion measurement purpose. While qualitatively successful, this technique has demonstrated that some erosion regimes produce coke layers on the surface of the material, which limits the accuracy of the measurement. But for a burning propellant on which this kind of difficulty is not present, the PCG method seems to be well suited for a local measurement similar to the one that can be obtained from an ultrasonic transducer. Strand[23] successfully employed this technique in erosive burning experiments. In addition, the first attempt carried out at the research level in France seems to be very promising; even if some work still to be completed to better understand the real influence of the plasma location near the propellant surface, the temperature sensitivity of the propellant electrical property, and to address some other technological issues. Meanwhile, it is expected that this method could be inexpensive and less restrictive than the ultrasonic method to be used on various propellants, as no adapted coupling material is mandatory.

An alternative technique based on a plane capacitor has also been tested in Italy. This technique, that is applicable only to non-metalized propellants, is still in a preliminary phase of development and is currently limited to atmospheric pressure conditions. It is not possible to conclude yet on its ability to carry out standard burning rate measurements.

Critical Assessment

This review encompassed several advanced methods for measuring steady-state propellant burning rate. A critical assessment of the non-intrusive measurement techniques is made, including operational limitations, temporal and spatial limits, steady-state burning rate uncertainty, cost, maturity, advantages, limitations, and prospects for use for routine ballistic testing. Since the baseline ballistic screening device considered in this study is the subscale test motor, the non-intrusive opinions must be considered in relation to its capabilities. Ultrasonic instrumentation is recommended for application to routine ballistic evaluation of propellants in research and industrial settings. PCG is recommended for further development and application as a ballistic characterization device. Acoustic emission technique is endorsed as a routine method for ballistic characterization of propellant strands, and for further development an application to full-scale motors for grain evolution monitoring. X-ray diagnostics and the microwave technique are not recommended as routine ballistics tools. A detailed assessment of these methods including state-of-the-art operational, temporal, spatial, and uncertainty limits is provided in the final report and future JHU/CPIA CPTR's.

Future Prospects for Non-Intrusive Techniques

A greater desire to understand combustion of solid propellants in recent years has encouraged the further maturing of non-intrusive techniques for measuring instantaneous burning rate. Many approaches based upon various physical principles exist for determining the burning rate of solid propellants. The WG 016 supports Zarko and Kuo[21] view that even though new breakthrough techniques using basic

principles could still be developed in the future, further advancements in burning rate measurements will depend largely upon improvements in the existing techniques.

One fundamental limitation of all techniques investigated is that they measure properties that are proportional to distance. Since the desired parameter of interest is burning rate, some thinking should be done on a measurement technique that is sensitive or proportional to the surface velocity instead of the displacement. This would bypass the uncertainties amplified in data when time derivatives are taken of displacement data.

Another future prospect for the recommended devices is the correlation of data from all sizes of tests. In principal, a test motor can be fired with ultrasonic instrumentation and PCG's in the laboratory, in production checks, on full-scale tests, and in flight. The PCG technology should receive priority for investment to mature this technique. This technology has great potential. If successful it could provide ballistic information at all points in the research, development, and use of solid rocket motors. The most practical aspect and recommendation of this work must be to encourage NATO nations to adopt ultrasonic instrumentation into their propellant development process.

TEST MOTOR SCALING

Accurate prediction of internal ballistics for the first full-scale solid propellant motor of a new design becomes increasingly important as motor size increases and fewer development motor firings are called for with success-oriented programs. The underlying reasons for the differences observed in burning rate between large-scale motors, subscale motors, strands and non-intrusive methods become apparent by considering the factors influencing propellant burning rate, which include Intrinsic, Global, and Contributing Parameters. The degree of scaling exhibited by strand burner, subscale or full-scale motor will vary in proportion to the effect exhibited by the influencing parameters. These effects are summarized here and reviewed in further detail in the final report[3] and JHU/CPIA CPTR 73[4].

The Intrinsic and Global Parameters influencing propellant burning rate dictate the differences observed in burning rate between large-scale motors, subscale motors, strands, and non-intrusive methods.[24] These parameters are summarized in Table 6.0. Intrinsic parameters are evident from a consideration of burning rate physics and models of burning rate mechanisms, and can be identified independently in the laboratory. Global parameters are derived from a consideration of the engineering design of the motor and its operating environment. Understanding and accounting for these parameters, in subscale hardware design serves to mitigate the scaling effects.

Table 6.0 Fundamental Factors Influencing Scaling of Burning Rate[24]	
A. Intrinsic Parameters	
	Pressure
	Temperature
	Propellant Mechanical Properties
B. Global Parameters	
1) Principal Factors	Internal Motor Flowfield
	Real Grain Geometry at Firing – Grain Deformation Effects
	Erosive Burning Effects – Cross-flow Velocity
	Rheology of Grain Manufacturing Process
2) Other Contributing Factors	Propellant Combustion Stability
	Radiation
	Propellant Composition at Propellant-Liner Interface
	Thermoelastic Coupling
	Nozzle Design
	Acceleration

Factors that should be <u>avoided</u> in subscale hardware that typically contribute to modeling complexity in larger diameter solid rocket motors include:[25]

1. High length to diameter ratio (L/D > 9)
2. Large axial pressure drop ((P > 100 psid at ignition)
3. Potential for erosive burning (Mach No.>0.4 in aft end at ignition)
4. Uncertainty in rheology (hump) response for new propellant and manufacturing process
5. Complex ignition process due to high L/D
6. Demanding customer specifications on trace shape reproducibility ($\forall$3%)

Industry Correlation Practices

Accuracy of solid rocket thrust-time prediction is important in solid rocket design. Propellant burning rate is one of the most significant variables in this prediction. An analytic methodology is recommended to correlating burning rate through performance prediction.

Early Scale Factor Approach

Historically "scale factor" has been a measure of the uncertainty to define the differences in burning rate between a subscale burning rate measurement device or subscale motor and a larger motor. The ratio of the full-scale motor rate to strand rate is a typical scale factor. Changes in scale factor between propellants tested in the same measurement systems sometimes vary on the order of 10%. Changes in scale factors for different propellants testing in different measurement systems can vary on the order of 15%. However, scale factor is much less variable within some undefined narrow range of formulation for a particular propellant; hence, its utility in predicting motors. Scale factor is generally considered a property of the subscale test device. Scale factor is a correction that must be applied to get the "right" rate due to different effects of influence parameters between devices. However, the definition is referenced to the predicted ballistics of the full-scale motor, so some consideration must be given the question of the accuracy of the prediction itself.

Modern Refinements

It was recognized that if the sources of some of the differences in burning rate between scales could be identified then the resultant uncertainty could be reduced; hence, reducing the "scale factor" dispersion. It is now recognized that scale factor has both constant and variable components. The scale factor usually discussed is the constant component, the ratio of the rate required to predict full-scale motor mean ballistics to the mean rate measured in subscale ballistic test motors. The variable component is the ratio of the instantaneous rate required to predict instantaneous full-scale motor ballistics to the mean rate required to predict mean full-scale motor ballistics. The variable component is usually defined, not in time, but in web thickness burned, and is probably best known as the "hump curve." A thorough means of predicting full-scale experimental results from theoretical analysis should include two correcting factors:

1. A constant, linear (web independent) correction often called Scale Factor, and
2. A variable, non-linear (web dependent) correction resulting mainly from the grain manufacturing process

Strand Burner-to-Motor Comparisons

The strand burner, while enjoying widespread use as a burning rate measurement device, has in recent times become less used as a tool for predicting full-scale motor performance. This is due in part to the fundamental problems reviewed in the final report. Correlations between strands and subscale motors are recommended in order to determine the influence of the controlling factors. Temperature sensitivity, σ_p, a propellant property, is easily measured in a strand burner and therefore can be compared among propellants without the influence of motor geometry. On the other hand, the temperature coefficient of pressure, π_k, is more easily measured in motors; it is the effect of initial propellant temperature upon motor operating pressure, as Kn is kept constant.

The strand burner is a better tool for measuring statistically significant effects of small formulation changes for quality control work, given proper test design and conduct. Limited success of cured propellant strands in certain applications led to the development of the acoustic emission method using liquid strands for improved discrimination capability over traditional strand pressure-time behavior. The full-scale rocket motor, subscale motor, liquid strand, or cured strands do not generally have the same burning rate at the same pressure, but it is possible to obtain a satisfactory correlation between them. The acoustic emission method has many advantages over the conventional nitrogen strand burning system.

Subscale-to-Full-Scale Comparisons

Strand Burner Correlations
Solid rocket motor performance predictions are possible by establishing a correlation between full-scale motor performance, subscale test motors, and liquid and solid strand burning rate tests. The confidence and accuracy of these predictions will be maintained if the correlation between motor performance and any of the subscale test methods remains constant.

The ultrasonic technique is currently used in France and the U.S. for screening and development of propellants for tactical applications. Excellent comparison is obtained between ultrasonic measurements in strands and pressure-time data for small and large motor firings. The unique advantages of the ultrasonic method is the number of tests are low (usually two), and it yields a continuous burning rate that can be used in ballistic codes.

Constant Motor Scale Factor
Constant scale factor data is supplied comparing large motor with subscale motor burning rates for Bayern-Chemie, Germany, RO Defence Rocket Motors, UK and a number of companies and motors from the U.S. Methods used to evaluate burning rate scale factor were summarized where available. Methods of evaluating scale factor may or may not attempt to account for some of the fundamental factors influencing scaling. Different motor manufacturers analysis methods seek to account for the fundamental factors controlling burning rate differently. This emphasizes that the scaling experience of a particular motor manufacturer is not generally applicable to another because of industry-wide differences in subscale devices, test methods and analysis methods.

Variable Motor Scale Factor
SNPE, France and various companies from the U.S. supplied variable motor scale factor data. Both France and the U.S. employ correcting factors to predict full-scale experimental results from theoretical analysis as previously recommended for thorough scaling definition, including a constant correction called Scale Factor, and a variable correction called Global Hump Effect (SNPE), Surface Burn Rate Error (SBRE) curve (Thiokol), or Hump curve (Aerojet).

Both France and the U.S. seem to seek different means of accounting for the principal parameters that contribute to differences in real motor internal geometry with scale. Both possess models for internal ballistic/structural/CFD flowfield-grain interaction. SNPE combines deformed grain structural response and erosive burning response characterization into their Global Hump Factor; while the US companies identify the separate contribution of these two effects on the SBRE or Hump Curve. Both countries use similar methods to account for the 2-D spatial burning rate mapping due to propellant rheology effects. Results support the finding that scaling experiences of a particular motor manufacturer may not be compared without accounting for these industry-wide differences in subscale devices, test methods and scaling analysis methods.

FUTURE DEVELOPMENTS[26]

Factors crucial to industrial acceptance are cost effectiveness and robustness. Until recently, ballistic test motors were focused on burning rate characterization. However, passive motor stability diagnostics provides concurrent modal frequency and stability margin estimates from low level pressure oscillations

present. Therefore, the cost effectiveness of the ballistic test motor *as a propellant charactizer* can be increased by nothing more than increasing the sensitivity of the pressure measurements.

On the other hand, hydraulic motors (variable volume pressure control via water venting from a closed high pressure tank) eliminate need for high strength case and nozzle, and provide stable operation to a power law exponent of n=1.5 (2 if cavitating ventury vent employed). Naturally adapted to high pressures by volume requirements, these devices "fit" current needs for higher pressure operation in many tactical situations. Although limited to smaller grains (1C2-4 grains were tested this way at Thiokol/Huntsville), these grains become "strands" by many safety standards, thereby offering "motor" tests in the propellant development lab, with a further corresponding cost savings.

The Parrs[27] have demonstrated the taut wire strand burning technique. In this technique the burning surface is held in a fixed position by a taut, refractory material fiber and its motion (driven by a constant force spring) is determined by a sensitive length detector (e.g., linear potentiometer, or LVDT). This robust and inexpensive servo-positioner technique provides three new functions: (i) continuous burning rate measurement, (ii) opportunity for concurrent direct burning rate difference measurements (reference motion to other strand), and (iii) concurrent burning surface temperature measurement (make the taut fiber a resistance thermometer or thermocouple). It should be noted that all three functions can be executed simultaneously.

Any new techniques will require a re-examination of propellant characterization technique and hardware as well as operational development. For example, ballistic test motors having characteristic frequencies in regimes of interest will be desirable; this will necessitate new geometric configurations. In a similar way, the ability of the taut wire technique to enhance the accuracy of sensitivity measurements, the key to empirical formulation development, by 40%, will instigate the development of instantaneous, multiple, simultaneous rate difference measurements in a variable pressure environment. Lastly, concurrent measurement of burning rate, sensitivities, and stability related information offer potentially valuable interactions. The ZN methodology, for example, connects steady and nonsteady behavior. Therefore, with both steady and nonsteady information in hand, other information can be accessed.

The refinement of current techniques, the development of innovative techniques and necessary theoretical accessories will provide excitement and improved solid rockets in the future. Detailed solid rocket simulations in progress will assist these potential developments. A fully coupled ballistic test motor simulation, for example, would demonstrate the effects of (i) cure shrinkage and grain temperature on the web, (ii) the effect of ordered particle distributions near the case and bore, (iii) combustion efficiency dependence upon heterogeneity, etc., and (iv) connect low level pressure oscillations with physical processes.

CONCLUSIONS

The NATO RTO AVT WG 016 has identified areas for improvements in burning rate measurement and analysis methods. Results support the finding that manufacturer burning rate data may not easliy be compared without accounting for industry-wide differences in subscale devices, test methods, and scaling analysis methods.

The advantages and disadvantages in the two fundamentally different families of burning rate determination merit continuing study. Historical preferences seem to dictate which methods are used. Analytical reasons exist for their application in specific situations. The large variability in burning rate definitions makes assessment of the analysis methods difficult. Some consistency in these definitions would promote ease in correlating data internationally.

A wide array of motors, each with uniquely different design features, exists for measuring burning rate within the countries surveyed. The predominant configuration encountered is the circular, center-perforated grain in the weight classes under 5000g. While the 5x10 cm (2x4 inch) motor is the most widely used tool, this motor is also not standardized with respect to dimensions and propellants mass, which varies between 120g - 450g. The WG recommends standardizing this motor by increasing the web of the propellant grain to nominally 13mm, resulting in a propellant weight of approximately 300-

400g. This would cover the majority of propulsion applications and allow greater international cooperation in correlating burning rate data. Further attention to refining experimental methods in order to reduce motor variability is warranted.

The round robin approach using simulated motor data has contributed successfully to pointing out the quality of applied data reduction methods for a change of several parameters (i.e. bore offset, characteristic length, non-neutral trace shape, rate equation, etc.) influencing combustion. Results from different procedures were compared with the rate equation used for the simulations and with each other to identify systematic errors inherent in the various procedures. The Hessler-Glick r_{HG} reference procedure avoided all the errors inherent in currently used TOT or MB procedures, obtaining data accurate to the basic time resolution of the simulations. However, these were *simulations*, and the simulations did *not* include several phenomena that occur in real motors. In real test motors, non-idealities in principal, favor the class of MB over TOT methods and somewhat restrict the accuracy demonstrated by HG in ideal cases. The WG recommends further development of the promising Hessler-Glick analysis procedure. An automatic HG procedure for use on standard desktop computers for the benefit of industrial manufacturers is recommended.

The WG surveyed the member countries on non-intrusive measurement techniques emphasizing those currently employed, including ultrasonics, x-ray, microwave, plasma capacitance gages, acoustic emission, and laser recoil. Ultrasonic instrumentation is recommended for application to routine ballistic evaluation of propellants in research and industrial settings. PCG is recommended for further development. The acoustic emission technique is endorsed as a routine method for ballistic characterization of propellant strands, and for further development in applications to full-scale motors for grain evolution monitoring. X-ray diagnostics and the microwave technique are not recommended as routine ballistics tools. Recommendations are provided for improving existing techniques, which can provide for further advancements in burning rate measurements.

A thorough means of predicting full-scale experimental results from theoretical analysis should include two correcting factors, a constant scale factor correction, and a variable correction resulting mainly from the grain manufacturing process. Solid rocket motor performance predictions are possible by establishing a correlation between full-scale motor performance, subscale test motors, and liquid and solid strand burning rate tests. The confidence and accuracy of these predictions will be maintained if the correlation between motor performance and any of the subscale test methods remains constant.

Many countries and facilities use only a constant scale factor correction. Various companies in France and the U.S. include the recommended variable motor scale factor correction, but seek different means of accounting for the principal parameters that contribute to differences in real motor internal geometry with scale. An effort to agree on consistent scaling methods would contribute to success in international cooperative programs.

The NATO RTO AVT WG 016 activities have acted as a catalyst for efforts to improve burning rate measurement and analysis methods within the NATO community. The WG recommends as a minimum, the NATO propulsion community review these findings as a means of advancing their own burning rate measurement and analysis methods.

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